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Conference Title

Modelling of Coastal Aquifers of Trivandrum

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Abstract

Trivandrum is one of the fastest growing cities of South India. The degree of landscape modification being made along the coastal zone of this city will be reflected in the quantity and quality of the coastal water resources. To combat the present threats, like the excess groundwater extraction and reclamation activities in the coastal regions of Trivandrum district, it is necessary to develop a groundwater management model. These models, will aid to project the behaviour of coastal groundwater system with respect to the future environmental challenges and to evolve suitable measures to control the saltwater intrusion into coastal aquifers of Trivandrum. The area selected for study is from Karikkakom to Pozhiyur region towards south of the coastal belt of Trivandrum. The main objectives of this paper is to develop a numerical model for groundwater flow and contaminant transport using Visual modflow and SEAWAT and to predict the groundwater heads and extent of intrusion during 2011-2020 through scenario analysis.

Keywords : Groundwater flow model,Contaminant Transport model

1. Introduction

Many coastal areas in the world are dependent on local fresh ground water resources because of heavy urbanization. Intrusion of saltwater is the most common pollutant in coastal aquifers. Intrusion of saline

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water occurs where saline water displaces or mixes with fresh water in an aquifer. Over pumping of groundwater wells that located near the shoreline is a major cause of encroachment of saline water into the aquifers. Extent and pattern of saltwater intrusion can be obtained by various solute transport models such as SUTRA, SEAWAT, FEEFLOW, MODFLOW etc. To combat the present threats, like the excess groundwater extraction and reclamation of wetlands in the coastal regions, it is necessary to undertake a scientific study that focuses on the behaviour of the coastal groundwater system. The best tool available to help groundwater hydrologist to meet challenges of prediction is usually by a groundwater flow model [1]. This model, will aid to project the behaviour of coastal groundwater system with respect to the future environmental challenges and to evolve suitable measures to control the saltwater intrusion into coastal aquifers.

Madhavi Ganesan and S. Thayumanavan (2009) simulate the groundwater flow and solute transport in the coastal aquifer of Chennai using the United States Geological Survey three dimensional models MODFLOW and MT3D. Rana Amin Sulaiman Kharmah and Dr. Mohammad N. Almasri (2007) conducted a study on Optimal Management of Groundwater Pumping in the Case of the Eocene Aquifer, Palestine. Kumar A. Narayan , Carsten Schleeberger and Keith L. Bristow (2007) describes the use of a variable density flow and solute transport model, SUTRA, to define the current and potential extent of seawater intrusion in the Burdekin Delta under various pumping and recharge conditions. S Mohan and S K Pramada (2005) conducted a study on management of South Chennai coastal aquifer system using Non dominant Sorting Genetic Algorithm (NSGA) which deals with multi objective optimization

The objectives of the present work is to develop a numerical model and contaminant transport model for ground water flow for the coastal aquifers of Trivandrum using Visual MODFLOW, to predict the ground water heads in the study area for a period of nine years and to study the effect of pumping on intrusion.

2. Study Area

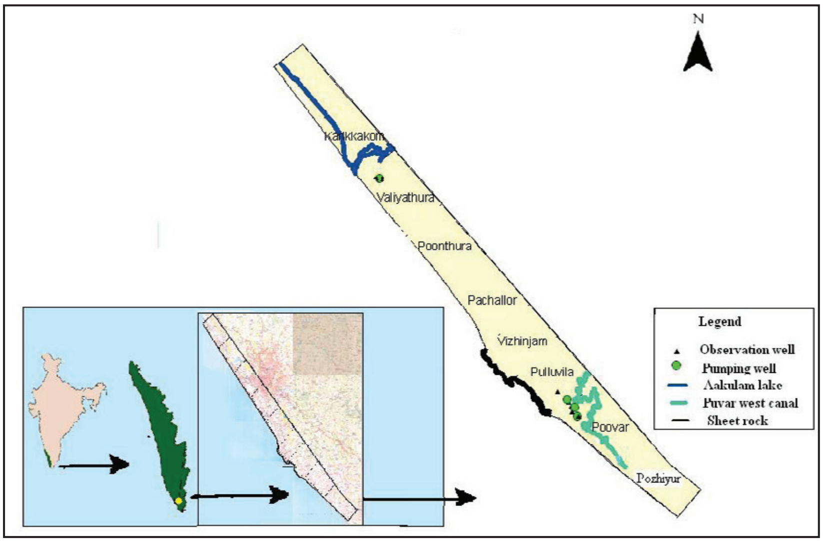

Fig. 1 Study Area

2.1. Data used

Drinking water requirement of this area is mainly met from groundwater sources through bore wells constructed by the Kerala Water Authority. Locations of the pumping wells and pumping rates during pre monsoon and post monsoon period obtained from Kerala Water Authority are given in Table I. In order to study the effect of pumping eight observation wells are selected and their locations are given in Table II.

Table I Pumping rate of pumping wells
(Source: Kerala Water Authority)

Well id	*Pumping well location*	*Pumping rate (m^3/day)*	
		Pre monsoon	Post monsoon
W1	Adimalathura	780	580
W2	Pulinkudi	288	216
W3	Chowara	540	405
W4	Karichal	2160	1620
W5	Valavunada	780	580
W6	Karikkakom	300	225

Table II Location of observation wells

Well id	*Latitude*	*Longitude*	*Location of Observation well*
OW1	$08^0$21’20.2”	$77^0$01’48.8”	Adimalathura
OW2	$08^0$21’21.3”	$77^0$01’48.8”	Adimalathura
OW3	$08^0$21’30.7”	$77^0$01’53.3”	Chowara
OW4	$08^0$21’10.5”	$77^0$02’02.8”	Karichal
OW5	$08^0$30’02”	$76^0$54’15.5”	Karikkakom
OW6	$08^0$30’2.3”	$76^0$54’17.8”	Karikkakom
OW7	$08^0$22’5.8”	$77^0$01’15.8”	Pulinkudi
OW8	$08^0$21’41.3”	$77^0$01’40.9”	Valavunada

For the development of numerical model, pumping rates of pumping wells, Lithological data, ground elevations at the well locations, weekly water level data of head observation wells are the model inputs. Lithological data of the study area obtained from the Central Groundwater Board (CGWB) is used to build the subsurface layers of the model. Based on this data model was divided in to 4 layers namely unconfined aquifer, Aquiclude, Aquifuge and Aquitard having thickness 28m,2m,10m and 14m respectively. Ground elevations of the well locations are obtained from fly levelling.

In this study chloride bicarbonate ratio is taken as the concentration of solute for contaminant transport model. Water quality data of observation wells during pre monsoon and post monsoon period is given in Table III. Chloride bicarbonate ratio of water samples collected from observation wells is greater than 0.5, which indicates that the groundwater is contaminated.

Table III Water quality data of observation wells

Well id	***Pumping well location***	***Cl /(HCO$_3$ + CO$_3$)***	
		Pre monsoon	Post monsoon
OW1	Adimalathura	1	1
OW2	Adimalathura	1	1.02
OW3	Chowara	1	1.02
OW4	Karichal	36	1.1
OW5	Karikkakom	1	0.9
OW6	Karikkakom	3	1.1
OW7	Pulinkudi	1.43	1.3
OW8	Valavunada	1.9	1.7

3. Methodology

Methodology mainly comprises of development of numerical model, contaminant transport model, prediction of groundwater heads and extent of intrusion under different scenarios.

3.1. Numerical model Development

Model development consists of converting the conceptual model of the coastal aquifers to a numerical model of groundwater flow using Visual MODFLOW. The governing equation for density-dependent groundwater flow model in terms of freshwater head, which is solved by MODFLOW routines in the SEAWAT code, derived by Guo and Langevin in 2002 is given by (1)

$$\frac{\partial}{\partial\alpha}\left\{\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial\alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\alpha}\right]\right\}+\frac{\partial}{\partial\beta}\left\{\rho K_{f\beta}\left[\frac{\partial h_f}{\partial\beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\beta}\right]\right\}$$
$$+\frac{\partial}{\partial\gamma}\left\{\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial\gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\gamma}\right]\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\bar{\rho}q_s \tag{1}$$

where α, β, γ are orthogonal coordinate axes, aligned with the principal directions of permeability $K_{f\alpha}, K_{f\beta}$ and $K_{f\gamma}$ are equivalent freshwater hydraulic conductivities in the three coordinate directions, respectively ,ρ is the fluid density , ρ_f is the density of freshwater , h_f is the equivalent freshwater head, Z is the elevation above datum of the center of a model cell S_f is the equivalent freshwater specific storage, θ is the effective porosity , C is the solute concentration $\bar{\rho}$ is the density of water entering from a source or leaving through a sink q_s is the volumetric flow rate of sources or sinks per unit volume of aquifer and t is time[2].

3.2. Contaminant Transport model Development

If the objective function and constraints for the optimisation problem involve solute concentration, a transport model must have also been developed using SEAWAT. The transport of solute mass in groundwater can be described by the equation (2)

$$\frac{\partial C}{\partial t} = \nabla.(D.\nabla.C) - \nabla.(\nu\, C) - \frac{q_s}{\theta} C_s + \sum_{k=1}^{N} R_k \qquad (2)$$

where D is the hydrodynamic dispersion coefficients, q_s is the volumetric flow rate representing sources and sinks, ν is the fluid velocity, C_s is the solute concentration of water entering from sources or sinks and R_k (k =1,……..N) is the rate of solute production or decay in reaction k of N different reactions. Chloride is the most dominant ion in the sea water and bicarbonate is the most dominant ion in the groundwater. So Cl /(HCO_3 + CO_3) is taken as the solute for contaminant transport modelling. Classification of groundwater based on chloride bi carbonate ratio is given in Table IV

Table IV Classification of groundwater based on chloride / (bi carbonate +carbonate) ratio (Source: Sankar R (2000))

Range of Cl/(HCO_3+CO_3) ratio	*Type of Groundwater*
< 0.5	Normally fresh groundwater
0.5 – 1.30	Slightly contaminated groundwater
1.30 – 2.80	Moderately contaminated ground water
2.80 – 6.60	Injuriously contaminated groundwater
6.60 – 15.50	Highly contaminated groundwater
>200	Seawater

3.3. Discretisation of study area

The model domain should be divided in to finite difference grid for simulation such that in the plan view, the model grid consists of 30 columns and 30 rows. Fig. 2 shows spatial discretization of the numerical model.

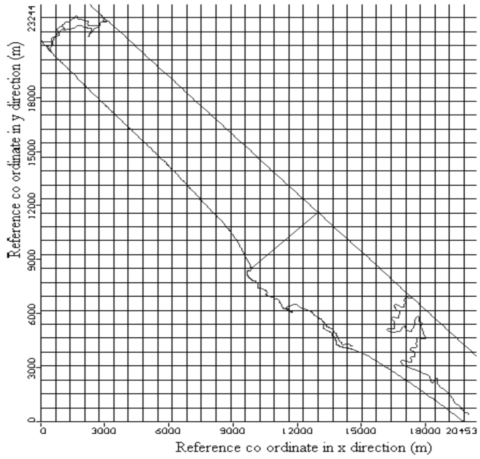

Fig. 2 Finite difference grid of the study area

3.4. Boundary Conditions

The boundary conditions of the model domain depend on many considerations, such as domain extent, water bodies and physical features within the study area. In this study river boundary, no flow boundaries, constant head boundary and recharge is defined for the flow model. Constant head cells are used to describe model boundaries with known heads such as aquifer contacts with major surface water features. For the flow model a constant head of 0m is specified for sea, no flow boundary for sheet rock region and river boundary for Aakulam Lake and Poovar west canal in the study area as shown in Fig 3.

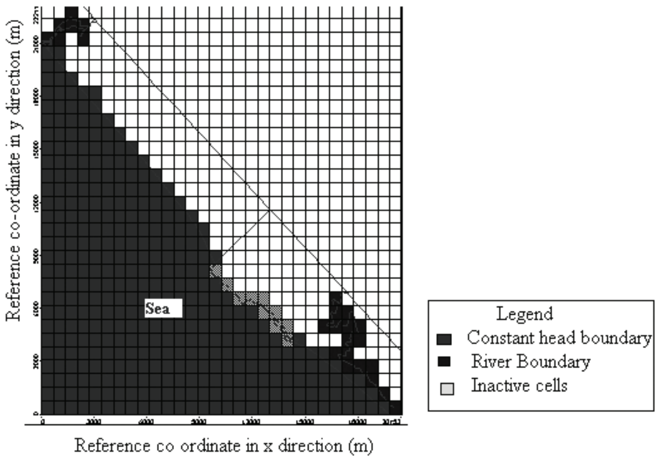

Fig 3. Boundary conditions of the numerical model

River boundary, no flow boundaries, constant head boundary, constant concentration boundary and recharge is defined for the contaminant transport model. For the contaminant transport model chloride bi carbonate ratio is taken as the solute concentration. A constant solute concentration of 200 is specified for sea, no flow boundary for sheet rock region and river boundary for Aakulam lake and Poovar west canal in the study area as shown in Fig 4.

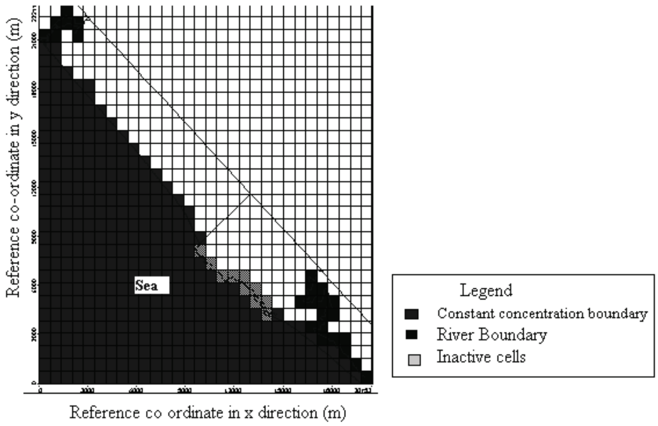

Fig 4 Boundary conditions of the contaminant transport model

The RECHARGE package, designed to simulate natural groundwater recharge to the groundwater system, was created using precipitation data, runoff, and actual evapotranspiration. Recharge from rainfall is calculated using the rainfall infiltration factor and was assigned to Layer 1. Rate of recharge from rainfall is given by

R = f x Normal rainfall in monsoon season

Where R – Recharge from rainfall

f - Rainfall infiltration factor

The rainfall infiltration factor for laterite soil recommended by the groundwater resource estimation committee (1999) is 0.07.

3.5. Model Calibration

Calibration is the process of finding a set of boundary conditions, stresses, hydrogeologic parameters and dispersivity values which produces a result that most closely matches field measurements and calculated value [3]. In this study calibration of numerical model is achieved through a trial and error approach by adjusting the zonation and values of two key parameters, hydraulic conductivities and specific storage, until the hydraulic head values calculated by Visual MODFLOW matches with the observed values. Calibration of contaminant transport model is achieved by adjusting the dispersivity values until a close match between the observed and calculated concentration values is obtained.

Observed hydraulic head values of each observation wells were measured from January 2010 to December 2010 are used for numerical model calibration. Model calibration is stopped when a reasonable match between the observed and calculated heads is achieved. Chloride/ (bi carbonate+carbonate) ratio of all water samples of observation wells during pre monsoon and post monsoon period in 2010 is measured for calibration of contaminant transport model. Dispesivity values are changed until a reasonable match between the observed and measured solute concentration is attained.

3.6. Prediction of Groundwater head and extent of saltwater intrusion

Once the model is calibrated, it can be used for prediction, which is the purpose of the most modelling efforts. Groundwater heads and extent of intrusion during 2011 – 2020 were predicted by the simulation model developed under transient state for different scenarios.

4. Results and Discussions

Calibration of the ground water flow model is done by varying the hydrogeologic parameters for each layer till a reasonable good match between the observed and calculated heads are obtained Scatter plot showing the goodness of fit between the observed and calculated heads is shown in Fig 5 and hydrogeologic parameters of different layers of the study area obtained after calibration is given in table III.

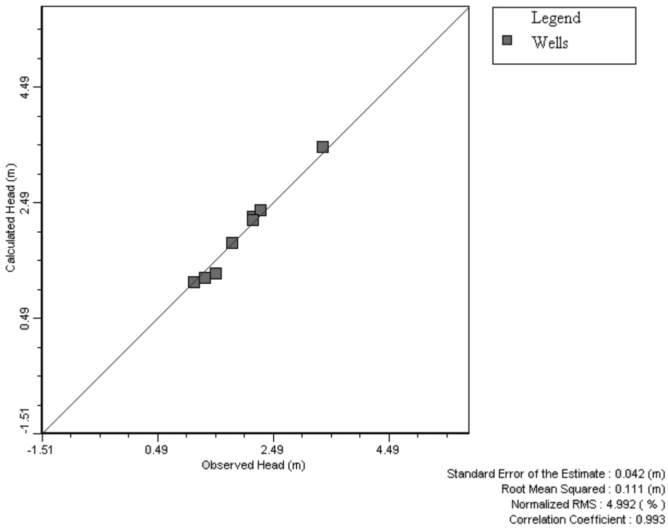

Fig. 5 Scatter plot showing the goodness of fit between the Observed and calculated heads

After model calibration an overall correlation coefficient of 0.993 and normalized RMS value of 4.992 % is obtained which indicates a reasonable good match between the observed and calculated heads.

Table III Calibrated Parameters of groundwater flow model

Layers	*Hydraulic conductivity (m/day)*	*Specific storage (m^{-1})*	*Effective porosity*	*Total porosity*
Unconfined Aquifer	33	1.4 x10^{-5}		
Aquiclude	0.5	5x10^{-7}	0.15	0.3
Aquifuge	0.05	0.0006		
Aquitard	8	0.0006		

Weekly water level data of observation wells from January 2010 to December 2010 was used as observation heads in the model. The model was run in transient state to yield calculated heads for observation wells in the study area for the same period. Fig.6 shows the simulated and observed heads of observation well at Adimalathura.

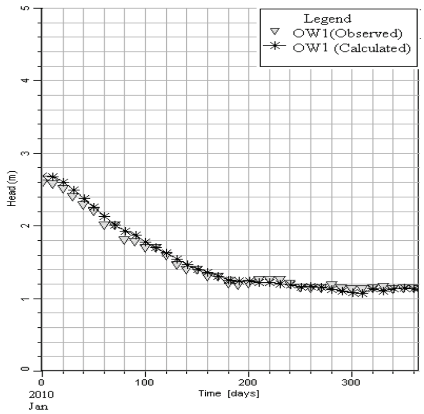

Fig 6 Simulated and observed heads of OW_1 at Adimalathura

After simulation it is seen that observed and simulated heads at all observation wells follows the same trend as that of observation well at Adimalathura.

Model calibration of contaminant transport model is done by adjusting the values of dispersivity until a reasonable match between the observed and simulated solute concentration is obtained. Scatter plot showing the goodness of fit between the observed and calculated concentration is shown in Fig 7 and dispersivity of different layers of the study area is given in table IV.

Table IV Calibrated Parameters of contaminant transport model

Layers	Dispersion (m)	Horizontal dispersivity	Vertical Dispersivity	Diffusion Coefficient (m^2/day)
Unconfined Aquifer	0.5	10	2	
Aquiclude	0.8 10	20	4	0..05
Aquifuge	150 20	20	4	
Aquitard	50 20	90	18	

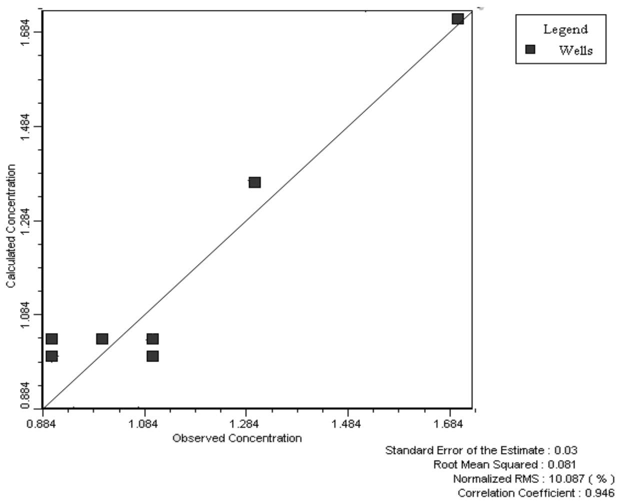

Fig. 7 Scatter plot showing the goodness of fit between the Observed and calculated concentration

After model calibration an overall correlation coefficient of 0.946 and normalized RMS value of 10.087 % is obtained which indicates a reasonable good match between the observed and calculated concentration [2].

Trivandrum, the Capital city of Kerala is growing at unprecedented rates, creating extensive urban landscapes. This results an over exploitation of groundwater resources and alteration to the land use/land cover pattern. Many of the farmlands and wetlands have been transformed during the past years into human settlements. Fig 8 shows the comparison of landuse pattern of study area in 1967, 1993 and 2008.

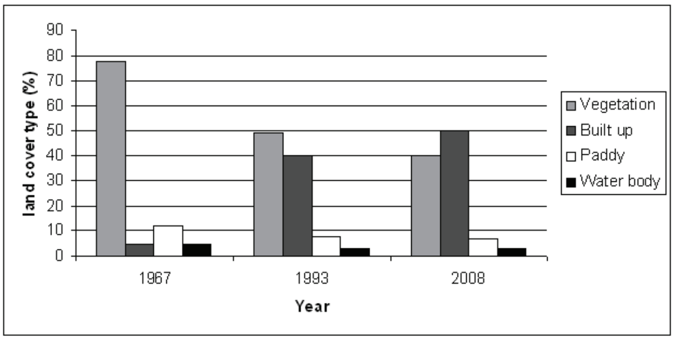

Fig 8 Comparison of Landuse pattern of study area in 1967, 1993 and 2008

In 1967, 78% of the total area is covered under vegetation, 12% is paddy, 4% is water body and only 5% is built up. In 1993, the area covered under vegetation get reduced to 49%, paddy fields reduced to 8%, water bodies reduced to 3% and the built up area increased to 40%.In 2008 area covered under vegetation get reduced to 40%, paddy fields reduced to 7% and water bodies reduced to 3%. Due to these reductions in vegetation, paddy fields and water bodies the built up area get increased to 50%. From this it is seen that due to rapid urbanisation there is a decrease in paddy fields, vegetation and water bodies resulting in an increase in built up. This in turn results in the declination of groundwater heads and thus enhancing the problem of saltwater intrusion into coastal aquifers.

Scenario I - Increase in pumping rate for every year by 1%

Due to rapid urbanisation prediction of ground water heads and extent of saltwater intrusion are done by assuming 1% increase in pumping for every year by keeping the boundary and field conditions same for ten years as those in January 2010 to December 2010. Fig. 9 to Fig.16 shows predicted head in each observation wells for 10 years.

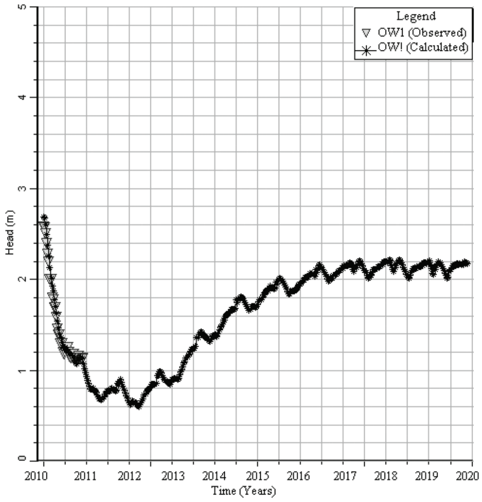

Fig.9 Predicted head in OW_1 at Adimalathura

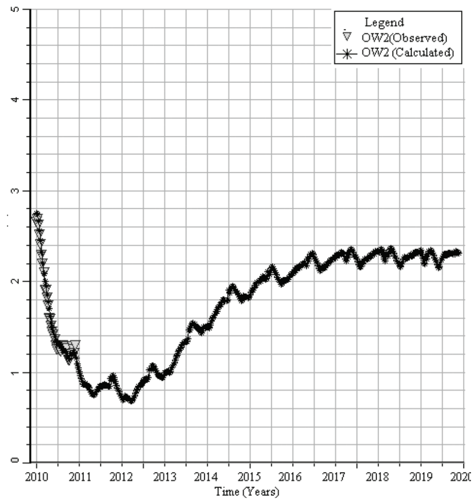

Fig.10 Predicted head in OW_2 at Adimalathura

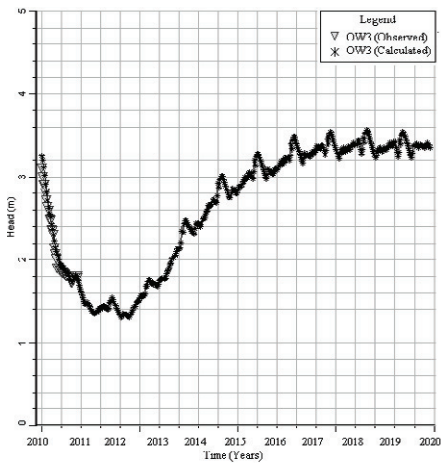

Fig. 11 Predicted head in OW_3 at Chowara

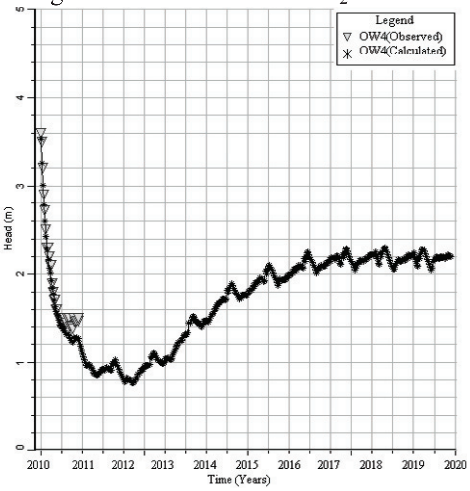

Fig.12 Predicted head in $0W_4$ at Karichal

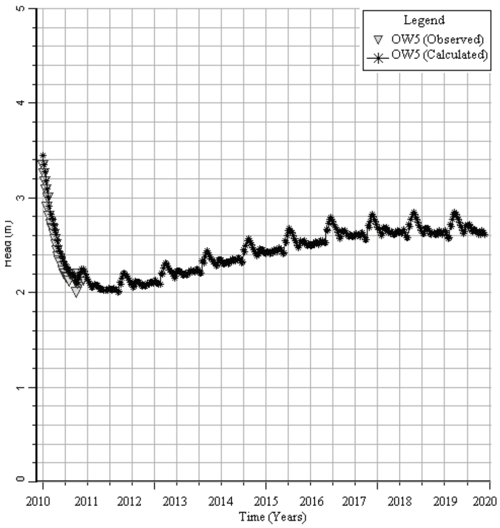

Fig.13 Predicted head in OW_5 at Karikkakom

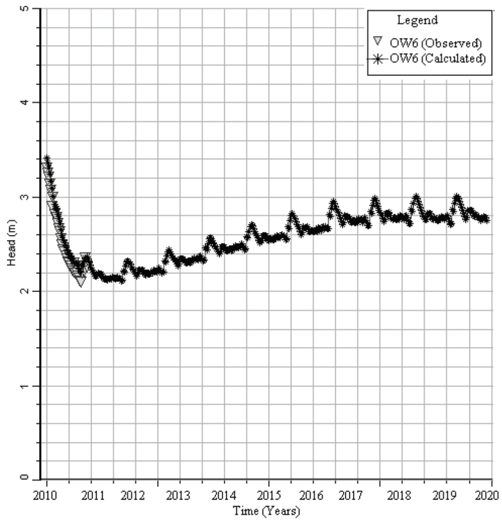

Fig.14 Predicted head in OW_6 at Karikkakom

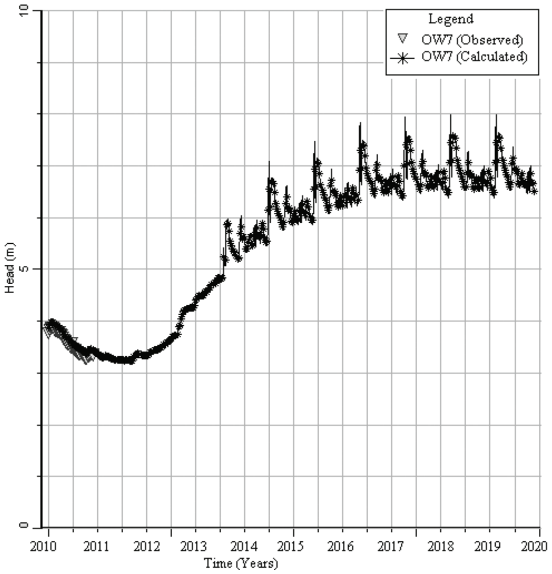

Fig.15 Predicted head in OW_7 at Pulinkudi

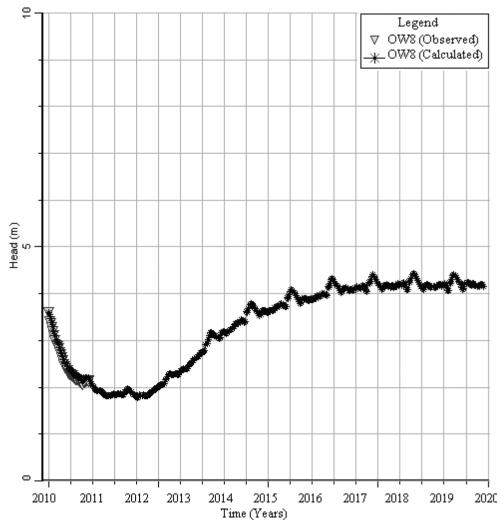

Fig.16 Predicted head in OW_8 at Valavunada

Predicted ground water heads in all observation wells shows a decreasing trend except observation well at Chowara (OW_3), Pulinkudi (OW_7) and Valavunada (OW_8). Increasing trend of the groundwater heads in observation wells at Chowara (OW_3), Pulinkudi (OW_7) and Valavunada (OW_8) is mainly due to the lower elevation of the observation wells compared to the pumping well in that locations and also due to the effect of nearby river. High rate of ground water recharge in these location also alleviate the negative effects of pumping.

Due to1% increase in pumping the groundwater heads decreases and as a result the extent of saltwater intrusion increases. In this study chloride /(bi carbonate + carbonate) ratio is taken as the indicator of saltwater intrusion. If the chloride /(bi carbonate + carbonate) ratio is greater than 2.8, groundwater is injuriously contaminated. . In order to find the lateral extent of saltwater intrusion the distance from the shore to the location where the chloride/(bi carbonate + carbonate) ratio is 2.8 is measured for each pumping well. The distribution of chloride /(bi carbonate + carbonate) ratio at Karikkakom pumping well location due to 1% increase in pumping in 2011 and 2020 are shown in Fig 17 and Fig.18.and at all other pumping well locations follows the same trend as pumping well at Karikkakom.

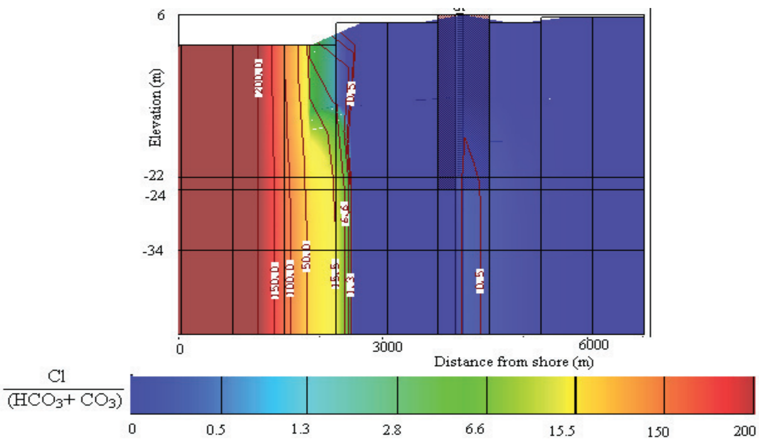

Fig 17 Distribution of Chloride/(bi carbonate +carbonate) ratioat Karikkakom pumping well in 2011

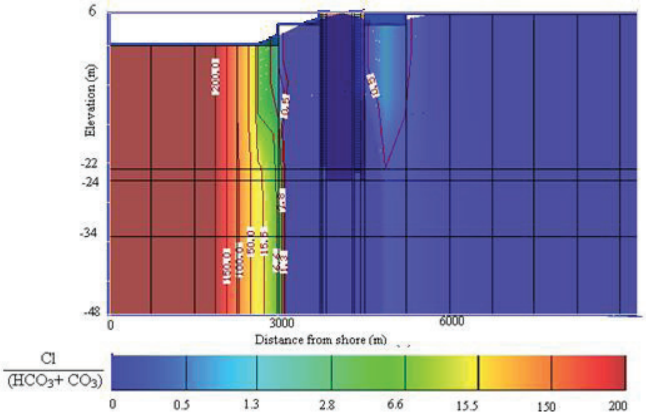

Fig 18 Distribution of Chloride/ (bi carbonate +carbonate) ratio at Karikkakom pumping well in 2020

Table V Lateral extent of saltwater intrusion due to 1% increase in pumping conditions

Pumping well Location / Year	Lateral extent of saltwater intrusion (km)	
	1% increase in pumping	
	2011	**2020**
Karikkakom	1.378	1.459
Pulinkudi Valavunada	1.054	1.216
Adimalathura Chowara Karichal	1.135	1.216

Table V shows the lateral extent of saltwater intrusion in all well locations due to 1% increase in pumping. In 2020 lateral extent of saltwater intrusion at Karikkakom pumping well location is found to be 1.459 km and at all other well locations, it is found to be 1.216km.As the pumping rate increases the cone of depression at Karikkakom spreads to Parvathy Puthanar, which is a polluted water body due to anthropogenic activities. Hence lateral extent of intrusion is more at Karikkakom when compared to all other well locations.

5. Conclusion

A numerical model was developed for groundwater flow and contaminant transport model in transient state using Visual MODFLOW .Groundwater heads in the observation wells near the pumping wells are predicted for ten years (2011 – 2020) using the observed water levels in the observation wells for a period of one year. A contaminant transport model was developed using SEAWAT and the effect of 1% increase in pumping on intrusion was studied. Predicted groundwater heads in most of the observation wells shows a decreasing trend. This decreasing trend in groundwater heads creates a landward hydraulic gradient which leads to saltwater intrusion in to the coastal aquifers of Trivandrum. The lateral extent of saltwater intrusion is more at Karikkakom pumping well location when compared to all other well locations due to 1% increase in pumping.

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